Bias in Ponded Infiltration Estimates Due to Sample Volume and Shape

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ABSTRACT

Estimates of saturated and unsaturated water flow in soil are important for predictions of infiltration, runoff, and solute transport. Previous research indicates that ponded infiltration estimates are influenced by the volume or cross-sectional area of the measurement. Our study compared quasi-steady infiltration measurements made using 20-, 30-, and 45-cm-diameter cylinders driven 25 cm deep into 56 field plots under diverse agricultural management practices. Mean infiltration rate increased from 50, to 81, to 95 mm h^{-1} as diameter increased. Standard deviation and range also increased with diameter. All three diameters produced lognormal data distributions. These results indicate that increasing the sample area is not equivalent to pooling of many smaller samples, which would have produced the same mean but with a lower variance. Follow-up experiments with a double-ring configuration or a divider placed in the center of a 45-cm cylinder demonstrated that adding vertical barriers reduced infiltration even when the total infiltration area was unchanged. A pulse of dye introduced 10 min before removing the ponded water showed an extensive network of dyed flow pathways in all but the slowest infiltration situations. The pathways were not associated with visible macropores. Careful consideration should be given to the dimensions of samples used to estimate saturated and possibly unsaturated flow from infiltration experiments.

Infiltration rate measurements are key components of many soil, hydrogeologic, and environmental investigations. Infiltration rate is often used to estimate saturated hydraulic conductivity (K_s), a critical parameter in numerical models for surface hydrology, variably saturated flow, and contaminant transport.

As a matter of convenience, typical soil water flow measurements are made using small soil samples, often intact soil cylinders of <10-cm diameter. Some investigators have compared measurements made on different size samples and found substantial differences in mean infiltration rates. Youngs (1987) found a lower variance, but a higher mean infiltration rate when the diameter was increased from 3.5 to 91 cm for rings driven 2 to 5 mm deep. Sisson and Wierenga (1981) showed that 5-, 25-, and 127-cm-diameter rings gave similar mean infiltration rates, although the mean increased from 6.25 to 8.48 and 8.51 cm d^{-1}. Davis et al. (1999) compared constant-head well permeameter, 6- by 7-cm cores, and 20- by 30-cm cores, and found that the largest core size gave estimates from one to three orders of magnitude greater than the other two methods. Air permeability measurements have been similarly shown to be scale dependent, with estimates increasing as much as a factor of 20 when the scale of measurement increased from 0.1 to 2 m (e.g., Garbesi et al., 1996; Tidwell and Wilson, 1999).

Measurement bias related to sample size has sometimes been attributed to smaller samples having less probability of encountering spatially infrequent, high magnitude portions of the soil (Iverson et al., 2001; Starr et al., 1995). As pointed out by Sisson and Wierenga (1981), however, this would be a violation of the central limit theorem, since the mean of randomly selected samples should be centered on the same value regardless of their sample volume. If a sufficient number of small-volume samples are used, the mean should be equivalent to that of larger samples. In terms of the variance, large-volume samples should be equivalent to pooling small samples, unless the measurement technique creates artifacts dependent on the volume or dimensions of the sample. To account for the decrease in infiltration measured with smaller infiltration rings, Shouse et al. (1994) suggested that a stagnation zone (an artifact of the measurement technique) was introduced when partitions were driven into the soil to contain and measure infiltration.

Many soil parameters, such as denitrification rate and water infiltration, are lognormally distributed (e.g., Parkin and Robinson, 1992; Grigal et al., 1991). If samples are pooled before measurement, or their individual measurements are averaged, the distribution of the means should be more normal than the distribution of individual samples (Quinn and Keough, 2002). For a soil variable that is randomly distributed at the spatial scale in question, measuring a larger volume of soil is equivalent to pooling smaller samples (Parkin and Robinson, 1992). Both the large and small volume sample data are then sampling the same population and will center on the same mean, but data from the larger samples will produce a lower variance and be closer to a normal, Gaussian, distribution. Data distributions from experiments by Shouse et al. (1994) and Sisson and Wierenga (1981), however, show no tendency toward normality with increased sample size.

Methods for measuring saturated flow are designed to restrict infiltration to a technically feasible soil volume. While below-surface flow paths are not explicitly part of an infiltration rate estimate, methods that either restrict or enhance flow will affect the infiltration estimates. It is known that detached cores can have much higher infiltration rates than those measured in situ (Lauren et al., 1988). This is because detached cores may have vertical pores that are open on the bottom, thus allowing water to freely exit the core, whereas flow in the field may be restricted below the sampling depth. Methods that permit subsurface lateral flow outside the ponded surface area may overestimate the infiltration capacity at the field scale, while methods that restrict lateral flow may underestimate the infiltration rate.

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Many studies using dye to trace water flow have found indications of preferential flow without the presence of large pores (e.g., Ghodrati and Jury, 1990; Omoti and Wild, 1979). Preferential flow may even occur at very low application rates (Andreini and Steenhuis, 1990; Dunn and Phillips, 1991; Flury et al., 1994; Radulovich et al., 1992; Vervoot et al., 2001). This means that a systematic measurement bias during saturated flow could also influence unsaturated flow estimates.

This paper reports on experiments designed to characterize the nature of the sample volume and geometric effects on ponded infiltration measurements made in situ.

MATERIALS AND METHODS

The experiments were performed on one soil type under a wide array of agricultural management practices producing different infiltration capacities. In 16 of the 56 plots, after water infiltration a pulse of dye was used to trace preferential flow pathways. Two followup experiments tested hypotheses to explain the observed data distribution.

The experimental plots were located near Pendleton, OR (45°43′ N, 118°38′ W, elevation 458 m). Annual precipitation averages 420 mm and falls mostly as rain during the winter. Temperatures average −0.6°C in January. Summers are hot and dry, with an average temperature of 21°C in July. The soil was Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll containing about 18% clay, 70% silt, and 12% fine to very fine sand). Infiltration measurements were made in two sets of field plots. One was a rotation of winter wheat (*Triticum aestivum* L.) and summer fallow established in 1931, and the other was winter wheat in rotation with pea (*Pisum sativum* L.) established in 1967. The experimental plots were chosen because they provided a wide array of soil management practices and also simultaneous winter wheat crop and winter wheat stubble. Pikul and Allmaras (1986) measured bulk density in the winter wheat–summer fallow plots and found a tillage (plow) pan at the 19- to 29-cm depth, with a maximum bulk density from 1.21 to 1.31 Mg m^{-3}, depending on residue management treatment. Above the pan, bulk density ranged from 1.17 to 1.26 Mg m^{-3}, and below the pan, at 39 cm, bulk density was 1.09 to 1.12 Mg m^{-3}.

History, C and N balances, yields, and other factors of the winter wheat–summer fallow experiment can be found in Rasmussen and Parton (1994), and individual treatment effects on infiltration, aggregate stability, earthworms, and glomalin found in Wuest et al. (2005). The 40 winter wheat–summer fallow plots were 12 by 40 m. A description of the pea–winter wheat experiment can be found in Wuest (2001a). Briefly, ponded infiltration was correlated with soil carbon, aggregate stability, and glomalin. The two tillage treatments sampled in our investigation were plowing before planting both the pea and winter wheat vs. no-tillage planting for both crops. The 16 pea–winter wheat plots were 7.7 by 36.5 m.

Single-ring infiltration measurements (Bertrand, 1965) were made in March 2003 for the winter wheat–summer fallow plots and in March 2004 for the pea–winter wheat plots. In both cases, the soil was near field capacity as a result of natural precipitation. Three measurements were made in each plot, each using a different diameter cylinder (20-, 30-, and 45-cm diameter). Row spacing of the wheat crop (and subsequent stubble) was 25 cm, so cylinders were placed to always include at least one row inside the measurement area even in the 20-cm cylinders. Cylinders were driven into the soil about 25 cm, and the soil around the inner circumference of the cylinder tamped with a 4-mm-thick plot stake to seal any gaps between the cylinder wall and the soil column. Previously collected rainwater was used to avoid effects of salts, since these dryland fields never receive irrigation. The water level was maintained at approximately 5 cm above the average soil surface for 30 min. Thirty minutes was found to be sufficient time to approach steady state ponded infiltration. Then at least 20 min of infiltration measurements were taken using either depth gauges or calibrated water reservoirs supplying float valves. The final rate measured was considered sufficiently stable for comparison of the three simultaneous measurements. To verify this, extended intake curves were measured in April 2005 in one of the winter wheat–summer fallow plots and one of the no-till pea–winter wheat plots. Two cylinders of each diameter were measured in each of the two plots. In this paper use of the term *infiltration rate* refers to this quasi-steady state infiltration rate. In every plot the three cylinder diameters were run at the same time and for the same length of time. Soil and water temperatures during measurement were generally 8 to 12°C.

Following ponded infiltration measurements in the pea–winter wheat experiment, a concentrated solution of blue dye (C.I. Food Blue 2; C.I. 42090; *N*-ethyl-*N*-[4-[[4-[ethyl[(3-sulfophenyl) methyl]amino]phenyl](2-sulfophenyl) methylene]-2,5-cyclohexadien-1-ylidene]-3-sulfobenzenemethanaminium hydroxide inner salt, disodium salt; $C_{37}H_{34}N_2Na_2O_9$–S_3) was added to bring the water to >4 g L^{-1}. After 10 min the dyed water was suctioned off with a vacuum hose until no ponded water existed on the soil surface. About 24 h later, the cylinders were excavated in 5-cm layers. Each depth was carefully scraped clean of smeared dye and photographed. An alternative to scraping the excavated surface would have been to pull the core from the soil, set it on its side, press the core from the cylinder, and break off lengths of core to take photographs of untouched soil (Wuest, 2001b). This allows very fine pores to be observed, but natural horizontal fracture planes sometimes exaggerate the dye patterns. Scraping the exposed soil surface obliterates fine pores, but gives a better representation of how the dyed water moved in the vertical direction. Allowing the cylinders to drain for 24 h made it easier to excavate the layers without smearing the dye onto unstained soil, but it also means that the dye stains represent not only ponded infiltration during the 10-min exposure but also a certain amount of redistribution. Clear differences between samples from soils under different soil management practices were evident even after 24 h, and our experience with cores excavated immediately after dye removal is that the dye patterns are not qualitatively different from patterns seen after 24 h.

Concentric Cylinder and Divided Cylinder Experiments

The concentric cylinder and divided cylinder experiments were performed in a no-till plot of the pea–winter wheat experiment, a treatment where high infiltration rates had been measured previously. The new measurements were made in August 2004 after pea harvest. In the concentric cylinder experiment, a traditional double-ring infiltration arrangement (Bertrand, 1965) was used with a 20-cm cylinder placed inside a 45-cm cylinder. The cylinders were initially driven to a 10-cm depth and ponded for 2 h. The inner, 20-cm cylinder was subsequently driven to 15-cm, and later to 25-cm depth. Then the outer, 45-cm cylinder was driven to 15 and 25 cm. After each depth change, infiltration rates were measured. Four replicate double-ring setups were run simultaneously, along with four 30-cm single cylinders driven progressively from the 10-cm depth to the 20- and 25-cm depths for comparison.

In the divided cylinder experiment, six 45-cm cylinders were driven to the 25-cm depth and ponded for 2 h. Then 1-mm-

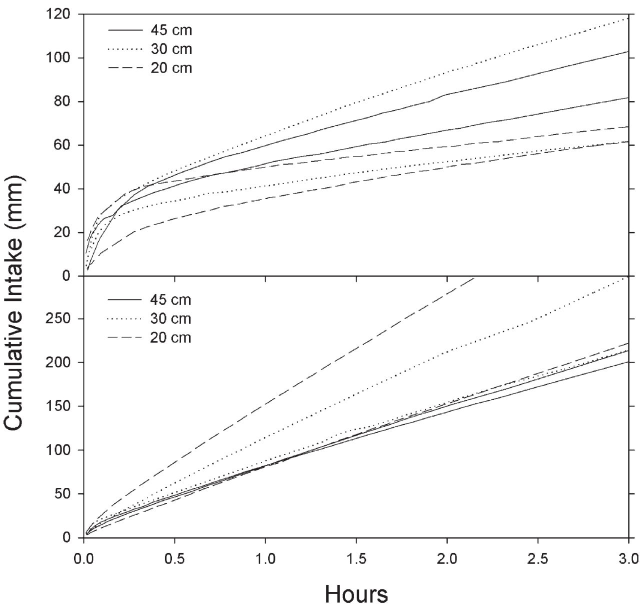

Fig. 1. Intake curves for one winter wheat–fallow plot (upper graph) and one no-till pea–winter wheat plot (lower graph). In both plots two cylinders of each diameter were measured for 4 h, at which time the wetting front was well below the bottom of the cylinders. The lines were plotted as straight segments between data points without smoothing or averaging. Infiltration rates in this experiment were measured between 0.5 and 1 h.

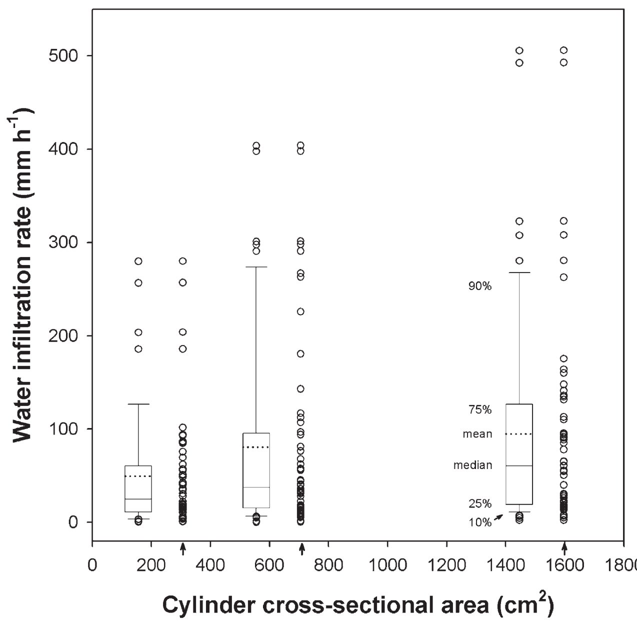

Fig. 2. Ponded quasi-steady state infiltration rates measured using cylinders of 20-, 30-, and 45-cm diameter (306-, 705-, and 1596-cm^2 cross-sectional area) driven 25 cm deep. The three measurements were made side by side in 56 research plots (n = 56 for each diameter) with treatments ranging from seedling winter wheat planted into plowed summer fallow to wheat stubble in a no-till, pea–winter wheat rotation. Box plots are shown to the left of each data set.

thick metal plates with sharpened leading edges 43 cm wide were gently inserted across a diameter of four of the cylinders. The depth of the dividing plates was incrementally increased from 5 to 10, 15, 20, and 25 cm. Measurements of ponded infiltration rate were made after each change in divider depth and at similar times for the two cylinders without dividing plates.

Analysis

The data were examined with an emphasis on comparing the distributions produced by the three different cylinder diameters. Since the three diameters were always measured close together, at the same time, and for the same length of time, they represent a balanced treatment set. The individual soil management treatments of the experimental plots are not of particular interest here, except that they allowed the data set to represent a wide array of infiltration capacities. Therefore, the main statistical analysis was a Shapiro-Wilk test for lognormality (SAS Institute, 2002). Since log transformation and analysis of variance are commonly used to analyze lognormal data, this information is provided also, with the reminder that log transformed analysis of variance compares the estimated medians, not the means of the three populations. The mixed model analysis used the Satterthwaite degrees of freedom method (SAS Institute, 2002). In this research (and most other infiltration research) individual infiltration samples are not the subjects of interest, but are instead intended to estimate the average infiltration of an entire field. Therefore, differences between means were compared using confidence intervals computed using the uniformly minimum variance unbiased estimators method of Land (Parkin and Robinson, 1992).

RESULTS

The extended intake curves demonstrate that all three cylinder diameters attained near steady state infiltration at or before 30 min (Fig. 1). There are also no obvious differences in early intake characteristics between the different diameters.

Figure 2 shows the distribution of data from measurement of all 56 plots using 20-, 30-, and 45-cm-diameter cylinders. All three cylinders produced lognormal distributions (Shapiro-Wilk test $p < w = 0.0001$ or less) with means much greater than medians and long, positive tails. Standard deviations (Table 1) increased with cylinder diameter, even though the 30-cm cylinder represented 2.3 times the volume, and the 45-cm cylinder 5.2 times the volume of the 20-cm cylinder. More importantly, the estimate of infiltration rate on a unit area basis almost doubled from the 20-cm to the 45-cm cylinder diameter. The respective 10% confidence intervals overlap only slightly (44 to 87 vs. 83 to 145), which indicates a low probability (<10%) the two samples are from the same population (Parkin and Robinson, 1994).

Our data set represents the gamut of soil management practices used in dryland cropping: from intensive tillage to no-till, measured at the end of the rainy season (March) after planting wheat and also in undisturbed stubble. Figure 3 divides the same data set into two groups based on soil conditions producing fast and slow infiltration. The data demonstrate that the cylinder-diameter effect existed even where infiltration rates were slow. The means increased with cylinder diameter, along with the 25th, 50th, and 90th percentiles. The standard deviations increased along with the means, producing nearly equal coefficients of variation (94–97%). Again, all data distributions were lognormal (Shapiro-Wilk test $p < w = 0.001$ or less). Confidence limits at 10% probability level shown in Fig. 3 overlap between

Table 1. Cylinder diameters and arrangements used in the experiments. Mean infiltration rates and standard deviations are for cylinders driven to the 25-cm depth. Confidence limits were calculated according to the uniformly minimum variance unbiased estimator method of Land (Parkin and Robinson, 1992).

							Confidence limits		Log transformed data	
Cylinder diameter and arrangement	Cross-sectional area	Ratio of area to 20-cm cylinder	Shape	*n*	Mean final infiltration	SD	Lower 10% CL	Upper 10% CL	Mean final infiltration	SD
	cm²				mm h⁻¹					
20 cm	306	1		56	50	63	44	87	3.16	1.36
30 cm	705	2.3		56	81	102	72	144	3.63	1.38
45 cm	1596	5.2		56	95	109	83	145	3.95	1.20
Concentric cylinder exp.										
30 cm	705	2.3		4	48	8				
20 cm inside 45 cm	306	1		4	20	9				
45 cm with 20 cm inside	1280	4.2		4	28	2				
Divided cylinder exp.										
45 cm	1596	5.2		2	196	47				
Divided 45 cm	1596	2.6 + 2.6		4	114	32				

the 20-cm and larger diameters. This means that at $n = 32$ or $n = 24$ we cannot establish with high probability that the means are from different populations. The same is true for the entire dataset shown in Fig. 2 and Table 1.

Log transformation and analysis of variance results in $p > F$ of <0.005 for soil treatment, stage in crop cycle,

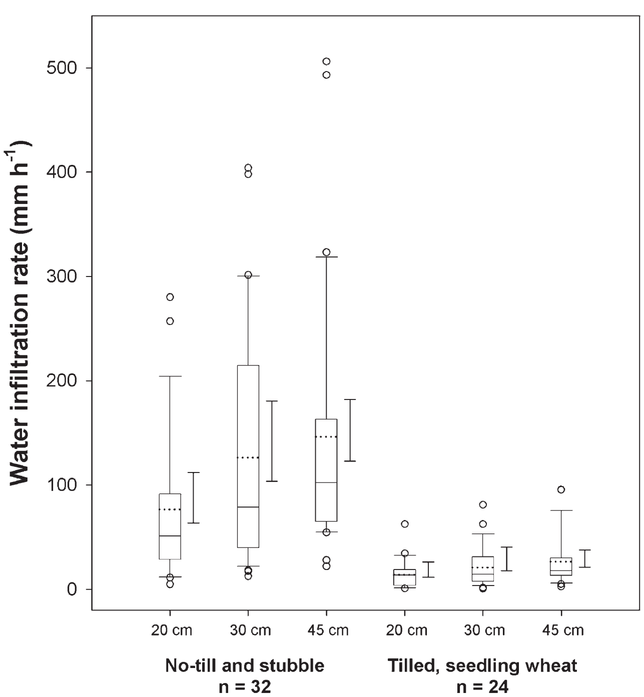

Fig. 3. Box plots of water infiltration data divided into treatment and crop status conditions producing high and low infiltration rates. Cylinders with diameters of 20, 30, and 45 cm were used in side-by-side measurements under diverse soil management practices. Error bars to right of box plots show upper and lower confidence limits at 10% calculated using the uniformly minimum variance unbiased estimator method of Land (Parkin and Robinson, 1992).

and cylinder diameter in both the winter wheat–summer fallow and pea–winter wheat experiments. A mixed model run on the combined data, with soil management treatments, crop cycle, and experiment designated as random effects and cylinder diameter the fixed effect, produced a probability of a greater t (absolute) value of <0.02 for differences between the mean of log transformed infiltration rates of the three cylinder diameters.

No-till treatments had high infiltration rates even in the spring (March) after planting winter wheat, probably because of soil protection and aggregation effects of accumulated surface residues. On the other hand, plowed treatments produced a finely pulverized surface soil with almost no surface residue and had low infiltration rates. At the end of the rainy season, the soil surface was smooth and somewhat compacted from the action of rain and freeze–thaw cycles. All treatments had greater infiltration rates while the wheat stubble was left undisturbed.

Dye patterns demonstrated obvious differences between greater and lesser infiltration rates. In rings measuring <35 mm h^{-1}, very little if any dye (ponded for 10 min following 2 h of non-dyed ponded infiltration) was present below the 5-cm depth. In cylinders measuring >100 mm h^{-1}, more than 30% of the soil was dyed at a depth of 10 cm. Two examples are shown in Fig. 4. The dye patterns (blue color in Fig. 4) consisted of patches of stained soil intermingled with patches of unstained soil. The patterns were not noticeably different among the three cylinder sizes. The locations of dyed patches were generally consistent from depth to depth in any particular cylinder, indicating mostly vertical flow paths. In cylinders with low infiltration rates the dye-stained patches decreased rapidly in area with increasing depth. In rings with high infiltration rates, dye-stained area remained almost constant from 10 cm to the bottom of the cylinder. Only 5 of the 48 rings showed possible in-

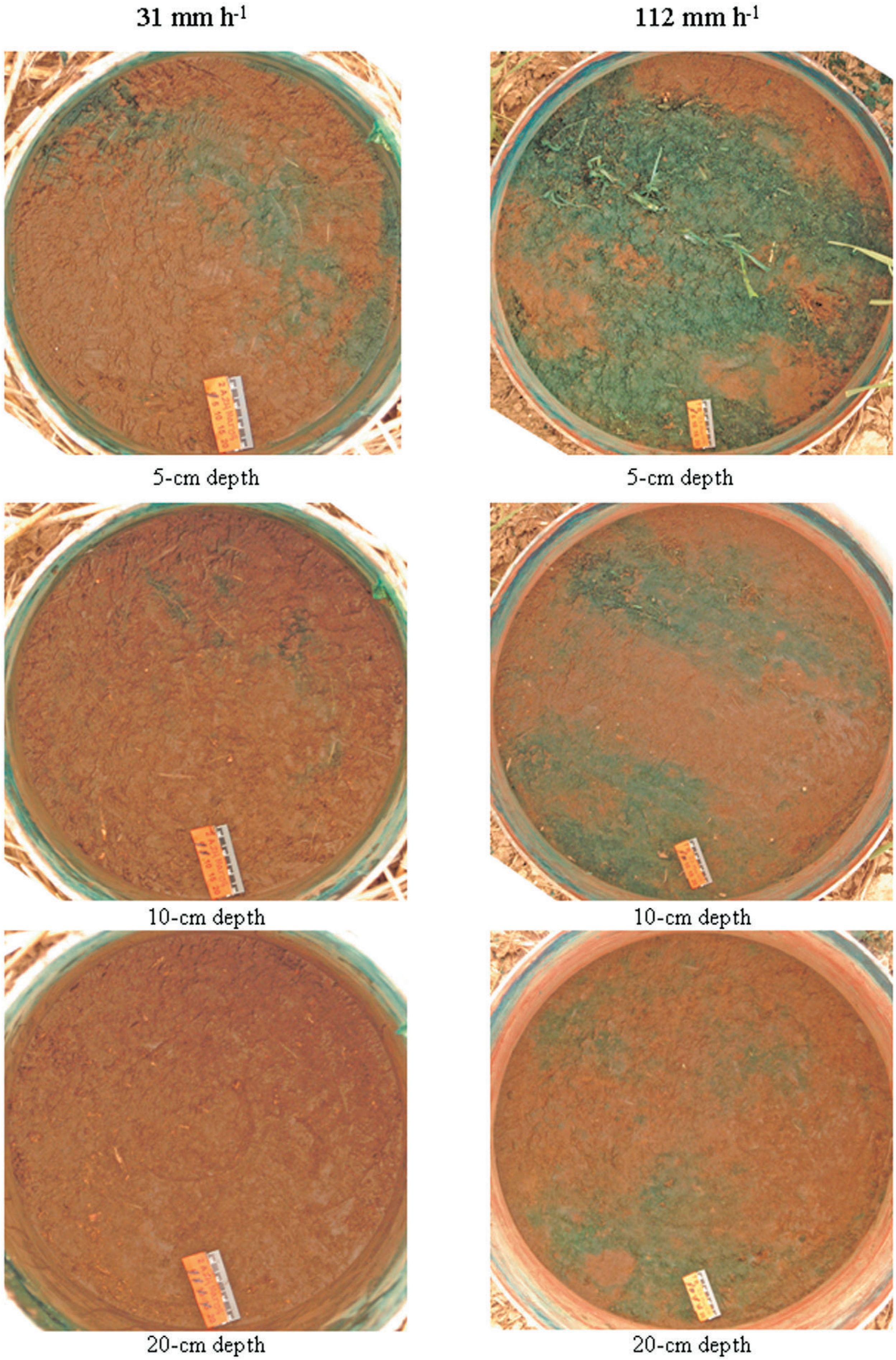

Fig. 4. Photos of cross sections from plots with high and low infiltration rates. The blue dye (not visible in black-and-white copies of this figure) was added to the ponded water for 10 min before the water was removed. The 31 mm h^{-1} example was a 20-cm diameter cylinder in a plowed treatment in wheat stubble. The 112 mm h^{-1} example was a 30-cm cylinder in a no-till treatment in seedling winter wheat.

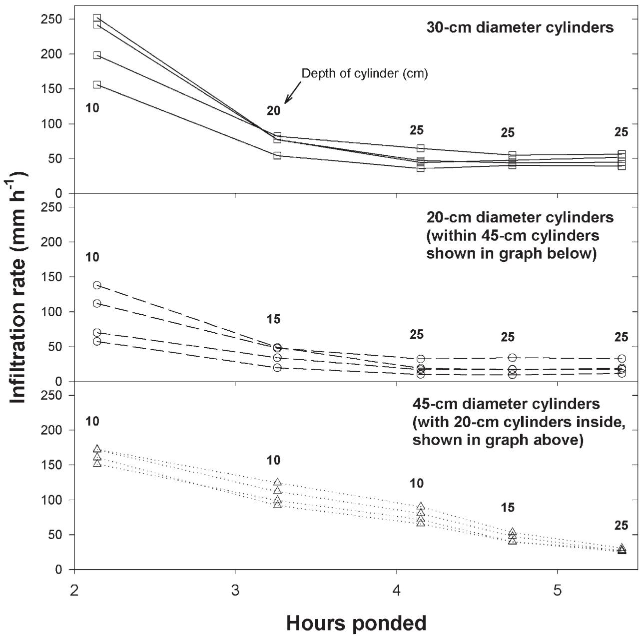

Fig. 5. Infiltration rate changes as cylinders are driven deeper into the soil in the concentric cylinder experiment. Numbers indicate the depth (centimeters) of the bottom of the cylinder at the time an infiltration rate was determined. The 30-cm cylinders were single. The 20- and 45-cm cylinders were concentric, as in a standard double-ring infiltration test.

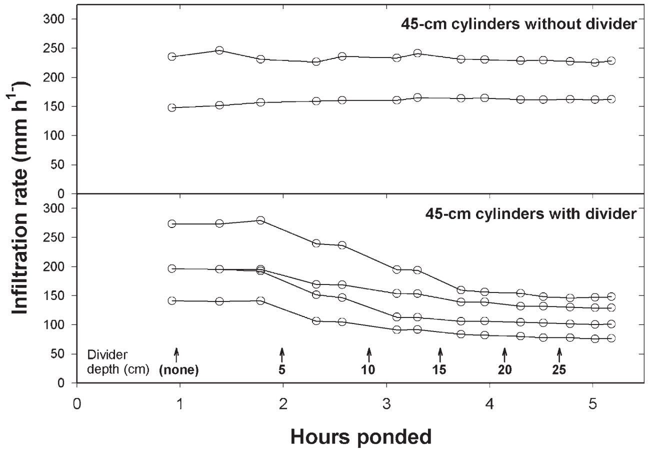

Fig. 6. Infiltration rate of 45-cm diameter cylinders driven 25 cm deep, with and without a sheet-metal divider gently inserted after quasi-steady state ponded infiltration was attained. Arrows show timing when the divider depth (cm) was increased. The vertical divider almost completely divided the soil in the cylinders across a diameter.

dications of either flow between the soil and the cylinder wall or restriction of flow due to compaction of soil near the cylinder wall.

Concentric Cylinder and Divided Cylinder Experiments

The concentric cylinder experiment was designed to test the hypothesis that the cylinder size effect is the result of the cylinder walls restricting water movement through lateral preferential flow zones. Driving cylinders progressively deeper did reduce ponded infiltration (Fig. 5). Driving a 20-cm-diameter cylinder progressively downward within a 45-cm cylinder reduced its infiltration rate similar to driving the 30-cm cylinder deeper. Even though the inner 20-cm and outer 45-cm cylinders were infiltrating water at the same time, driving the inner cylinder deeper decreased the infiltration rate of the outer cylinder. It should also be noted that this outer cylinder had almost twice the cross-sectional area of the 30-cm cylinder (Table 1), but had a much different cross-sectional shape and a lower infiltration rate at both the start and end of the depth changes (Fig. 5).

The divided cylinder experiment tested the hypothesis that a barrier to lateral flow dividing a volume of soil will reduce its infiltration capacity. Pressing a thin sheet of metal progressively downward to divide 45-cm cylinders progressively reduced infiltration rates until the sheet reached 10 to 15 cm (Fig. 6). Increasing the depth of the divider to 20 or 25 cm did not appear to significantly change infiltration.

DISCUSSION

The infiltration mean, variance, and range all increased with increasing cylinder diameter. Whether or not the 20-cm cylinder represented a sufficient representative volume to encompass variability within our soil, the larger cylinders should demonstrate a decrease in variance if the sampling is unbiased. The larger cylinders should also tend toward a less lognormal, more normal (Gaussian) data distribution. Instead, the data distributions (Fig. 2) clearly indicate that randomly selected samples produce different estimates of infiltration depending on the diameter of the measuring device. This bias in infiltration estimates exists under both low and high infiltration conditions (Fig. 3).

The dye indicated a random, mottled pattern of faster or "preferential" flow in all three cylinder diameters, supporting the assumption that even the smallest cylinders are sampling a randomly distributed variable. The dye also indicates that the differences in infiltration between diameters are not due to compression or disturbance near the cylinder wall, which could have been a greater factor in small vs. large cylinders. Statistically, the different means indicates that the three cylinder sizes are not sampling the same population, because they are not showing a central tendency. Since the three cylinders were always run in very close proximity to each other, at the same times, and under the same conditions for each plot, it appears that the cylinder size effect was an artifact of the measurement device, not a bias in sample location.

Differences in infiltration estimates might be attributed to the effect of the lateral matric flow forming a bulb below the bottom of the cylinder, which would affect a smaller diameter cylinder to a greater extent than a larger cylinder. This effect would be greatest in dry soil and in cylinders driven to a shallow depth, and only occur after the wetting front exceeds the cylinder depth. In this experiment the cylinders were driven deep enough so the bottom was embedded into or nearly into the plow pan, and the antecedent soil moisture was high. The data show that the larger diameter cylinders had greater quasi-steady state infiltration rates, which is contrary to a lateral matric flow effect.

The suggestion that smaller-volume samples have less probability of encountering rare, extreme portions of the soil is not supported for a measurement such as water infiltration if the cumulative surface area is the same. These measurements are made by quantifying the volume of water infiltrated into a certain area of soil. If a cylinder happens to be located over a high-flow area, such as a large, deep macropore, the calculated infiltration rate per unit sample area will be much greater for a small cylinder than for a large cylinder. This is because there is less area over which to average the high volume of intake. The same would be true of other flux measurements such as nitrification and gaseous flux. In our dataset the highest readings and the greatest variance were produced by the largest cylinders (Fig. 2). The increase in data range with increase in cylinder diameter indicates that zones of relatively high water flow function at greater capacity in large diameter cylinders than in small diameter cylinders.

The concentric cylinder and divided cylinder experiments indicate that restricting lateral flow by reducing the cross-sectional distances inside a cylinder tends to reduce ponded infiltration. In the concentric cylinder experiment, driving the inner cylinder deeper decreased infiltration in the outer cylinder. This means that even though the inner cylinder was ponded and infiltrating water at the same time, the outer cylinder was infiltrating water through soil under the center cylinder. Driving the inner cylinder deeper must have cut off transport routes previously available to the outer cylinder. Implications for fluid flow research are that small sample volumes or short dimensions systematically underrepresent saturated flow potential.

The idea that stagnation or restriction of flow downward is due to the insertion of the cylinder wall is not supported by inspection of dye patterns. Very few of the photos showed any indication that the patterns were influenced by the presence of the cylinder wall, even at distances of 1 mm or less. Shouse et al. (1994) were correct in concluding that the infiltrometer instrument alters the infiltration process, but the effect is probably not a zone of soil disruption. Our data indicate it is because flow is somehow blocked by the cylinder wall.

In our experiment, soils with both high and low infiltration rates were subject to cylinder-size bias (Fig. 3). This was not expected, because high infiltration rates are thought to be more dependent on preferential flow zones. Other researchers have demonstrated that soils are influenced by preferential flow and lateral connections during both saturated (or ponded) application rates and application rates low enough to prevent saturation of surface soil (Andreini and Steenhuis, 1990; Flury et al., 1994; Radulovich et al., 1992).

It might seem obvious that a 10-min pulse of dye would show deeper penetration in a soil with fast infiltration compared with a soil with slow infiltration. This is only necessary if piston flow is assumed. If structures similar to macropores are involved, the downward velocity of water in those pores might be uniformly high, the difference in infiltration rate depending only on the number of active macropores per unit area. The importance of the qualitative dye information presented here is that it confirms two important assumptions necessary to have confidence in the data. First, flow down the soil-cylinder wall interface or soil compaction due to driving the cylinders was not a factor. Second, the patterns of dye-stained soil did not appear to differ for different cylinder diameters.

CONCLUSIONS

Our research demonstrates that sample size and shape can have a substantial influence on estimates of saturated flow. Including larger cross-sectional distances within the sample volume consistently increased ponded infiltration rates. In our soil, increasing cylinder diameter from 20 to 45 cm increased ponded infiltration estimates by an average of 90% under both low- and high-infiltration soil management treatments. This sample-volume bias is an artifact of the measurement technique. Data distributions show that the phenomenon is not a result of larger sample volumes having greater precision. We hypothesize that sample volumes or shapes that restrict lateral flow reduce the natural movement of water through preferential flow paths, even in this weakly structured soil.

This study was limited to ponded infiltration. It would be valuable to know if a divider would reduce unsaturated flow in the same way as saturated flow. A tension infiltrometer could be set up and a vertical divider pressed in from the side. It would also be valuable to know if longer dye exposure would produce the same dye patterns in low infiltration-rate plots as those found in high infiltration-rate plots. Preferential flow, as indicated by dye patterns, appears to dominate water flow in situ, even under unsaturated conditions, and lateral flow may be a substantial component of infiltration under field conditions. The dimensions of these proposed flow networks are much larger than the dimensions of common laboratory and field soil core measurements.

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